Increasing Energy Efficiency of Mine Ventilation Systems

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ABSTRACT

Every year the United States mining industry spends millions of dollars on underground ventilation systems. In the U.S., fan systems used for mine ventilation consume approximately 12,000 million kWh annually (Xenergy, 1997, 1998). Potential motor-driven system energy savings can be realized by using mature, proven, and cost-effective technologies. Such saving potentials exist in the mining industry and the U.S. Department of Energy's Motor Challenge program aims to assist the industry in capturing them. Energy efficiency upgrades can also achieve significant non-energy benefits such as better equipment reliability, longer equipment life, reduction in maintenance costs and downtime, and an improved working environment. Improved energy efficiency typically leads to reduced environmental emissions. The Motor Challenge program promotes a "Systems Approach" rather than a "Component Approach" when evaluating projects for energy efficiency. A systems approach takes into account all the elements from the point the power is distributed into the motor to the actual process work done. Energy saving opportunities exist at all places in the system but not all of them are cost-effective. Depending on the application, these savings can be easily realized by properly sizing and streamlining the fan systems, using premium energy efficient motors, using speed control wherever applicable, defining a proper control strategy and implementing measures that reduce air wastage.

KEYWORDS

Mine ventilation, Energy efficiency, Systems Approach, Motor Challenge, Savings Potential, Life Cycle Costing (LCC), Adjustable Speed Drives (ASD)

INTRODUCTION

This paper presents the role the U.S. Department of Energy's (DOE) Motor Challenge program plays in increasing the energy efficiency of industrial motor driven systems. DOE is working with nine energy-intensive industries to increase their energy efficiency and Mining is one of those nine industries. Recent market assessment results show that annual electrical consumption for the mining industry is 44 billion kWh. Of this, approximately 90% is consumed by motor driven systems such as: fans, compressed air, and pumps (Xenergy, 1998). Further breakdown of this electrical consumption shows that fan systems used for mine ventilation consume approximately 12 billion kWh (Xenergy, 1997). Potential motor-driven systems energy savings can be realized using mature, proven, and cost-effective technologies. Energy saving opportunities exist in the mining industry and the U.S. Department of Energy's Motor Challenge program aims to assist the industry in capturing them.

The Motor Challenge program promotes a "Systems Approach" rather than a "Component Approach" when evaluating projects for energy efficiency. A systems approach takes into account all the elements from the point the power is supplied to the motor to the actual process work done. Savings opportunities exist at all places in the system, but not all of them are cost-effective. Depending on the application, these savings may be realized by properly sizing and streamlining the fan systems, using premium energy efficient motors, using speed control wherever applicable, defining a proper control strategy and implementing measures that reduce air wastage. Energy efficiency projects can also lead to significant non-energy benefits such as better equipment reliability, longer equipment life, reduction in maintenance costs and downtime, and an improved working environment. Another benefit is a corresponding reduction in environmental emissions.

The first part of this paper provides insight into the systems approach and relates it to the components of a mine ventilation system. The next part provides details of the technologies and tools available to operate a system at or near its maximum efficiency. The third part provides three demonstration project case studies involving fans and ventilation systems, two of which were completed by the Motor Challenge Program. The paper concludes with the anticipated future work.

LITERATURE REVIEW

Mine ventilation systems have been designed, built and installed for years. The technology is well documented and textbooks and handbooks are readily available (Hartman, et al., 1997). The U.S. Bureau of Mines has also published bulletins on mine ventilating principles and practices (Kingery, 1960).

Since the energy cost in mines is a small fraction (less than 5%) of the overall production costs, less emphasis is given to energy efficiency than to production and maintenance. Also "pumping additional air than necessary doesn't hurt", has been the general mode of operation because mining has historically been an occupation with a relatively high-risk level to human health. However, recent energy trends and emission regulations have led the mining industry to look at more energy efficient technologies. Kumar, et al. (1995) discusses optimum fan selection in multiple fan networks to minimize power consumption. Ray (1995) highlights minimizing main mine fan duct pressure losses at a test site. With the advent of sophisticated computational capability, mine ventilation systems can now be modeled to determine optimum performance (Oberholzer & Meyer, 1995).

Internationally, energy consumption in the mining industry has been receiving renewed interest. A recent report showed that mining accounts for 22% of Canada's total industrial energy consumption (Jaccard & Willis, 1996). A study on Polish mines highlights monitoring and control of main fans for minimization of power consumption (Krzystanek & Wasilewski, 1995).

SYSTEMS APPROACH

Installing the most efficient motor and selecting the highest efficiency fan does not necessarily guarantee maximum energy savings. A *Systems Approach* has to be adopted in the design, specification, installation, and operation of these fan systems. A systems approach takes into account all the parameters and the efficiencies involved from the point where power enters the motor drive system to the point where the fluid provides its required function (also termed as "wire to air"). Typical system hardware as shown in Figure 1, includes the power distribution into the motor, the motor starting and drive system, the controls, the motor itself, the mechanical coupling, the fan and the ventilation system.

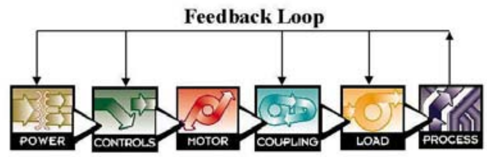

Figure 1. Typical Mine Ventilation Hardware

Figure 2 below shows an example of a fan system that illustrates the concept of a systems approach. In this example, the fan supplies ambient air for ventilation purposes. Control is accomplished with a downstream discharge damper.

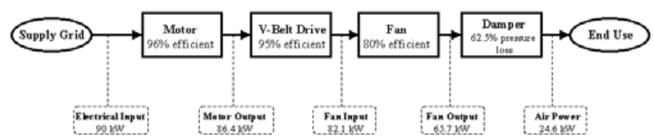

Figure 2. Fan Efficiency based on a Systems Approach Fan Flow rate: 66.1 m^3/s (140,000 cfm), Static pressure (at fan outlet): 1000 Pa (4.0 in. water), Static pressure (at damper outlet): 375 Pa (1.5 in. water)

As can be observed in Figure 2, although the individual component efficiencies for the motor, belt drive and fan are relatively high, the overall system efficiency is just 27%. This is because the pressure losses associated with the outlet damper control contribute significantly to the overall system performance. This example clearly demonstrates the need for using a systems approach instead of a component-based approach in considering potential upgrade options

Depending on the application, the systems approach offers a methodical solution to increasing the energy efficiency. The starting point is the evaluation of the ventilation requirements, the control strategy and the performance characteristics of the currently installed equipment. Sometimes it is a simple case of the fans being oversized to accommodate future needs. The solution may be to adopt a proper control strategy for multiple fans. It may also include the addition of an adjustable speed drive to reduce fan output based on shift times, occupancy, type of mining activity and other factors.

COMPONENTS OF A MINE VENTILATION SYSTEM

The main components of a mine ventilation system are:

- Power Supply
- Motor
- Coupling
- Fan
- Flow Control Devices
- Ducts, Passageways & other System Hardware

Power Supply

High voltage wires, transformers, switchgear and starters comprise the electrical hardware components. Most of the mining facilities receive the standard 3-phase industrial electricity from a local utility company. Associated with the electrical supply are three different types of charges: consumption charge (in $/kWh), peak demand charge (in $/kW), and a power factor penalty. The utility companies may also offer several combinations of rate schedules. Some mining facilities also generate their own electrical supply on site.

Motor

A motor converts the electrical input power into rotational mechanical output power; it has an efficiency associated with this conversion. The Energy Policy Act (EPACT) that came into effect in October 1997 requires most general purpose, polyphase, squirrel-cage, induction motors rated 0.75 kW (1 hp) through 150 kW (200hp) to meet minimum energy efficiency standards. Motors that have full load efficiency ratings higher than the prescribed EPACT standards are termed as *energy efficient* motors. The Consortium of Energy Efficiency (CEE) recognizes motors that meet a higher efficiency level than EPACT. These are termed as *premium energy efficient* motors. CEE works with its members, including a number of utility companies to provide incentives for purchasing these premium energy efficient motors.

Based on the load factor and the number of hours of operation, payback periods can vary significantly for replacement of standard motors by energy efficient models. Although the first cost of an energy efficient motor may be higher, the potential savings that can be gained accumulate rapidly over the life of the motor. On average, the initial cost of the motor operating in an industrial setting is probably 5-10% of its overall life-cycle operating cost, so a decision based solely on first cost considerations is usually an expensive decision.

The DOE's Motor Challenge program has developed a software package called MotorMaster+ (DOE, 1998) that assists in motor systems management. The software has a built in database of over 17,500 motors manufactured in the US along with their load and efficiency characteristics, installation and rewind costs, etc. The software is menu-driven, modular, and can be used for simple querying purposes as well as for more complicated batch analysis, etc. The software also includes tools for an economic analysis, an environmental energy accounting, conservation savings tracking, and greenhouse gas emissions reduction reporting.

Coupling

The coupling transmits the power from the drive shaft to the fan. For smaller sizes, a V-belt arrangement is frequently used. This has the advantage in that it is relatively easy to make fan speed changes if system requirements are different in the future. But belts have to be periodically tightened and adjusted to ensure proper alignment. Larger fans over 373 kW (500 hp) are almost always directly coupled with a gear or flexible disk type of coupling. For this arrangement, the fan speed is fixed to the motor speed. Other possible coupling arrangements are gearboxes and fluid couplings. Gearboxes have very little application to ventilation fans as they are more suited to high speed blowers. Fluid couplings are occasionally used on main ventilation fans and have the advantage of fan speed control.

Fan

Fans are classified into two main categories: centrifugal and axial-flow. Within each category there are many types, models, and arrangements. Centrifugal fans are further classified based on the curvature of the blades: radial, forward inclined, and backward inclined. Axial-flow fans can be further classified as tube-axial and vane-axial. Axial-flow fans are also classified by the impeller type: Fixed blades, Adjustable blades, and Variable-pitch-in-motion. Fan selection depends on the application and physical constraints of the site, and there are several handbooks and textbooks that provide this information (Bleier, 1998). Proper sizing and selection of a fan can lead to significant energy savings along with reduced maintenance costs and a longer life for the fan.

A mine can take years to be fully developed but the mine ventilation system is designed, built and installed up front. Clearly, the fan may be substantially oversized in the beginning, even if it is suitably matched to the fully developed mine requirements. For this scenario, the fan operating point may initially be far from its Best Efficiency Point (BEP).

Figure 3 shows a typical fan performance curve, its BEP, its design system curve, and its actual operating point (A) as may be typical during the early stages of a mine's development.

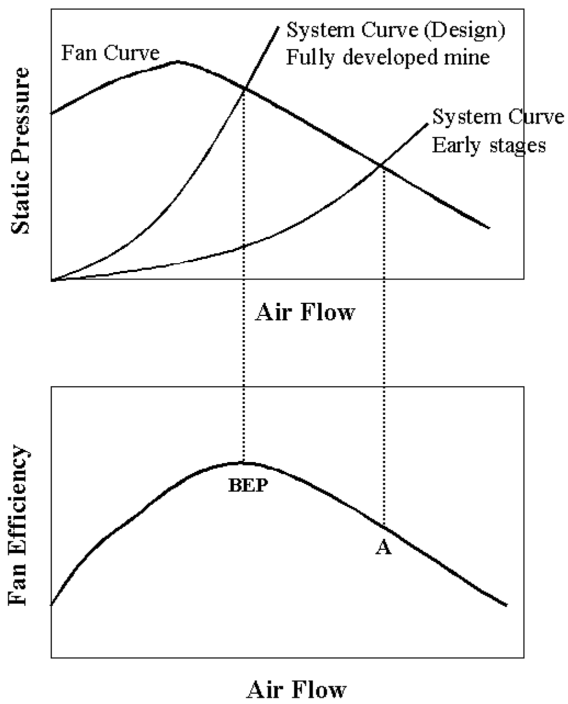

Figure 3. A Typical Fan Performance Curve and its Actual Operating Point

Flow Control Devices

Three types of flow control options are available for fans and each has applications in mine ventilation systems. The traditional method is the use of dampers. Several designs are available with the most common being inlet louver dampers, outlet louver dampers and variable inlet guide vanes.

Fan efficiency under damper control decreases with increasing amounts of dampering. Generally, efficiencies for the inlet louver and variable inlet guide vane designs are fairly high but they tend to decrease rapidly as flow reduces below 80-85%. This occurs because of the ability of the dampers to pre-spin the air.

Depending on the system operating points and the need for control, fan variable speed is an option that may be worthy of consideration. Speed control can be done by either electrical or mechanical methods. For the first case, it is accomplished upstream of the motor with a device that will vary the frequency of the electrical supply. These are called Variable Frequency Drives (VFD's). There are also several mechanical methods available that work on the principle of a controlled slippage between the fixed speed motor and the fan. One of the most common is a fluid coupling that is frequently used with higher horsepower fans. Both the electrical and mechanical methods will exhibit very high efficiencies across the operating speed ranges and thus provide significant energy savings at reduced flows. This occurs because of the relationship between fan speed, flow, pressure and power.

From the fan laws:

$$\text{Flow rate} \propto \text{Fan Speed}$$
$$\text{Fan pressure} \propto (\text{Fan Speed})^2$$
$$\text{Fan Power} \propto (\text{Fan Speed})^3$$

For fixed resistance systems that can handle the reduction in pressure that occurs with reduced speed, the fan power reduction is very remarkable. For example, 10% reduction in fan speed will result in a 27% reduction in fan brake horsepower requirements. In the latter part of this paper, a case study is presented that provides information of a VFD application.

A software tool, ASDMaster (EPRI, 1996), along with pre-screening capabilities is now available that helps to evaluate VFD applications. Two words of caution: Firstly, although VFDs are easy to operate and maintain, installation of VFDs has to be done in conjunction with a review of motor specifications and other sensitive electrical devices in the vicinity. Secondly, the practice of varying the speed of a fan that was originally designed for fixed speed operation should be checked out with the original fan manufacturer or a competent engineering company. In particular, the fan analysis will need to include an assessment of whether operation on variable speed will cause the fan to exhibit natural frequency problems, develop fatigue cracks or result in other compatibility concerns.

The third method of flow control in use for mine ventilation is variable-pitch-in-motion fans. With this type of equipment, the blades on axial-flow types of fans will adjust to meet the changing system requirements while in motion. There are many advantages to this technology including high efficiency and flexibility over a broad range of system operating points. The downside of variable-pitch-in-motion fans is their higher capital and maintenance costs and some added complexity of the fan.

Ducts, Passageways & other System Hardware

Fans are tested and rated according to certain standards and set-up configurations in the laboratory. However, in the field the set-up may be vastly different. Dampers, vanes, elbows, and other directional changes in the ducting systems play a significant role in determining the fan performance and the energy efficiency of the mine ventilation system. These system effects are manifested as a reduction in fan capacity and are reflected in the system curve.

The System Effect Factor (SEF) is a condition that causes deficient fan performance due to non-streamlined inlet and outlet designs. Its impact is calculated in inches of water and has to be added to the total system pressure loss in order to ensure proper fan selection. Standard guidelines are available from various sources to determine the SEFs for different operating conditions. Obviously, SEFs should be minimized to the greatest extent possible for the fan to attain peak performance.

OVERALL COST IMPLICATIONS & BENEFITS

As in every facet of life, the benefits (energy and non-energy) of an energy efficient installation do not come free. In most instances the premium is a higher first cost for a more efficient system but sometimes changes to the operating procedures may also be required. Traditionally people have ignored certain costs because they are difficult to quantify. A simple payback analysis is normally used during the decision-making process, but this is not appropriate for mine ventilation systems where the initial costs are a small fraction of the overall life-cycle costs.

The Life-Cycle Costing (LCC) approach provides the best solution for assessing the highest net present value of a system. The LCC technique provides the decision-maker with a powerful tool to estimate the overall expenses related to the operation and maintenance of the system over its life. The MotorMaster+ software has a built-in module to do a LCC analysis for motors.

Energy benefits are direct savings obtained from reduction of energy use, demand charge savings, and/or savings resulting from an improved power factor. Non-energy benefits may be more difficult to calculate and include environmental benefits (reduction of greenhouse gases), reduced maintenance costs and downtime, increased reliability and productivity, and an improved working environment. To establish the true benefits of a system during the decision making process both the energy and non-energy benefits should be considered.

CASE STUDIES

The DOE's Motor Challenge Program has undertaken several showcase demonstration projects in the past couple of years. These demonstrations target electric motor-driven system efficiency and productivity opportunities in specific industrial applications. These demonstrations show that the energy efficiency potential can be realized in a cost-effective manner. They are also designed to encourage replication at other facilities.

Three case studies that demonstrate increased energy efficiency in fan systems are presented in this paper. The first two (A and B) were done by the Motor Challenge Program.

A. Improving Ventilation System Energy Efficiency in a Textile Plant

The Fresno, CA cotton fabric plant of Nisshinbo California, Inc. uses nine supply fans and nine return fans. The fans are used to circulate high humidity air to maintain proper ambient conditions, cool process machinery, and control suspended particulate and airborne fibers. Initially, variable inlet guide vanes (VIVs) and outlet dampers controlled the system's airflow, but these proved to be highly inefficient. Setting these devices was imprecise and laborious and the VIVs and dampers experienced corrosion problems due to the high humidity in the air.

Applying a systems approach, the showcase demonstration team collected data on the system and developed a load duty cycle to establish energy demand, operating hours, and annual energy consumption. It was determined that the ventilation system's fans were significantly oversized. As a solution, fifteen out of the eighteen system fans were fitted with Variable Frequency Drives (VFDs). The damper controls were no longer necessary and the fan control dampers were opened 100%. The total electrical power demand fell from 322 kW to 122 kW and the total annual energy consumption fell from 2,700,000 kWh to 1,100,000 kWh. Some benefit also resulted from the reduced power factor penalty costs. The annual energy cost savings were $100,950 and the project implementation cost was $130,000.

On the non-energy benefits side, emission reductions of approximately 90909 kg (200,000 lbs.) of carbon equivalent per year were achieved through reduced motor energy consumption. VFDs provided plant personnel more control over the airflow and saved labor costs on the control of dampers. The air quality became easier to control as responses to minor variations in the ventilation requirements were now possible. Product quality improved and equipment breakdowns reduced because there was a decrease in the amount of airborne lint.

B. Improving Several Fan-Driven Systems in an Oriented-Strand Board Manufacturing Facility

Louisiana-Pacific Corporation, a producer of Oriented-Strand Board (OSB) in Tomahawk, WI, completed a fan system optimization project resulting in substantial energy and cost savings. The project involved optimizing three large motor-driven fan systems:

- Combustion air fan system
- Dryer induced draft fan
- Scrubber induced draft fan

Based on the feasibility study, several modifications were made to the fan systems. In the combustion air fan system, the control damper was removed and a 93 kW electric motor was replaced with a 30 kW high efficiency motor. The fan speed was also reduced from 2400 rpm to 1400 rpm. For the dryer induced draft fan, the flow damper was opened to 100%, a 261 kW motor was replaced with a 150 kW high efficiency motor and the fan speed was reduced from 1100 rpm to 700 rpm. For the scrubber induced draft fan, the flow damper was opened 100% and an inlet vane controller was installed to control the airflow.

This project resulted in electrical energy savings of 2,500,000 kWh annually compared to the earlier base-line electrical energy consumption of 5,700,000 kWh. The energy savings were worth $85,000 and the initial project investment was $44,000. Non-energy benefits included emission reductions of 673182 kg (1,481,000 lbs.) of carbon equivalent along with maintenance savings and improved reliability of the operation due to the reduced operating speeds of the fans.

C. Increasing Ventilation Without Increasing Power

A gold mining company in Canada required a ventilation rate of 141,000 cfm of air. But it was apparent that the two existing axial-flow fans were not providing enough supply air into the mine. The initial solution proposed was to replace the existing 150 hp fans with larger ones. However, when the actual flow was measured, it was found to be only 101,000 cfm. To achieve the specified flow would have required two 300 hp fans.

An engineering company specializing in fan systems was contracted to evaluate the options for increasing the airflow. When they conducted their inspections and tests, the following observations were made:

- The two fans had been mounted only inches apart from each other directly on the shaft bulkhead. No provision had been made to install outlet cones on the fans which would have allowed the proper development of flow and pressure before the air was dumped swirling into the mine shaft.
- The fans did not have inlet cones. This omission increases inlet losses and results in a poor flow profile into the fans.
- The fans were installed inside a heater house. Due to the configuration of the heater and the entry into the house, the air had to make a 90 turn just before the fan inlets.
- System performance tests indicated that the mine resistance was approximately 20% higher than design.
- A gap in the shaft collar was allowing approximately 4000 cfm to escape at the bulkhead.

Based on calculations associated with each observation, it was established that the two existing fans could meet the requirement of 141,000 cfm if a proper aerodynamically designed duct system was installed. This was completed and once the new inlet cones were installed, it was found that the reconfigured system met the 141,000 cfm airflow requirements. The cost of the new ductwork, inlet cones and relocation work was approximately $60,000. Most significantly however, the streamlined arrangement resulted in an avoided horsepower increase of over 300 hp. The savings on this avoided energy use are approximately $112,000/year.

CONCLUSIONS

Although the energy cost in the mining industry is a small fraction (less than 5%) of the overall production cost, savings from efficiency improvements can make a significant impact on the overall profit for the mines. The purpose of this paper is to highlight several energy saving opportunities in mine ventilation systems and present case studies where significant energy savings have been realized. The required technology and tools exist in the market to realize these energy saving potential opportunities. A systems approach complemented with a Life-Cycle Costing analysis has to be adopted for mine ventilation systems to provide energy efficient and cost-effective solutions. The improvements, though labeled as “energy efficient”, provide significant non-energy benefits including emission reductions, better equipment reliability, longer equipment life, reduction in maintenance costs and downtime, better working environment, etc. The U.S. Department of Energy’s Motor Challenge program along with the mining industry focuses on these improvements for motor-driven systems to increase the overall production efficiency of the U.S. Mining industry.

FUTURE WORK

In talking with several industry personnel and consultants about the problems associated with mine ventilation systems, the following items are evident:

- Ventilation system design are often based on a fully developed mine scenario and no considerations for part-load have been accommodated
- very little attention is paid to energy efficiency during ventilation system operation

The Motor Challenge program aims to work with the mining industry to undertake a systems approach to improve the energy efficiency of mine ventilation systems. One of the first steps in that regard is to undertake a study of ten to twelve mine ventilation systems in operation in the United States. For these mines:

1. Determine the theoretical air requirement based on current mine ventilation codes and standards.
2. Compare this theoretical requirement with the operating conditions. This would provide a baseline for mine ventilation systems in the United States.

Next:

1. Conduct feasibility studies and implement the technical improvements that will result in energy efficient system operation. Energy efficient options may include upgrades

that optimize equipment, control and system hardware. Analysis of existing codes may be required to establish if air requirements can be optimized.
2. Undertake another site evaluation to record energy savings and assess the project success.
3. Develop case studies and success stories that can be replicated in other mines.

These studies would also determine some best practice approaches for the selection, installation and operation of the mine ventilation systems.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Vestal C. Tutterow, P.E. of Lawrence Berkeley National Laboratory, Washington D.C. for his comments and review of the paper.

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